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Cold Regions Research and Engineering Laboratory

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Benefits of Using Remotely Operated Vehicles to Inspect USACE Navigation Structures

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Abstract: The U.S. Army Corps of Engineers operates numerous navigation locks and dams across the country. Age and lack of funds to maintain these structures has led to significant increases in unscheduled outages. Dewatering provides the best inspection opportunity but is costly and halts navigation traffic. Diver inspections are costly, and safety is an issue. Frequent underwater inspections using remotely operated vehicles (ROVs) would help reduce the number and severity of unscheduled outages at low cost, with little impact on navigation and few safety concerns. ROV use was documented at two Corps facilities and one public utility district and their costs were compared with inspections using divers or dewatering. In each case, benefits from reduced labor costs, shipping delays, and lost power production far exceed the amortized costs of the ROVs. The payback period for purchasing an ROV can be less than one year, and their easy deployment encourages more frequent inspections. ROV technology can immediately help to improve Corps asset management and public safety assurance through increased underwater inspections. Most Corps navigation facilities should own a small ROV, costing about $30K, to conduct visual inspections. Also, the Corps should partner with vendors to improve ROV internal navigation and to integrate real-time position, sensor data, and visual images within 3-D virtual representations of its structures.

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Preface

This report was prepared by James H. Lever, Gary E. Phetteplace, and Jason C. Weale, Force Projection and Sustainment Branch, Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army Engineer Research and Development Center (ERDC), Hanover, NH.

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Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
inches	0.0254	meters
knots	0.5144444	meters per second
pounds (mass)	0.45359237	kilograms

1 Introduction

The U.S. Army Corps of Engineers operates over 240 navigation locks at 195 sites across the United States. More than half of these locks are over 50 years old. Each site also has a dam to regulate water levels through the navigation channel. In 2004, downtime for unscheduled maintenance at Corps navigation facilities was 46,000 hrs, nearly equaling that for scheduled maintenance (Kidby 2006). It is common for the cost of the physical repairs to navigation structures to be less than the cost of shipping delays at these same structures. This situation is likely to worsen as the infrastructure ages and shipping traffic increases.

The vast majority of the Corps' multi-billion dollar investment in navigation structures lies underwater during normal operation, making routine inspections difficult. The significant increase in unscheduled maintenance at these structures suggests that underwater inspections are not occurring as frequently as prudence would dictate. The Corps also operates numerous flood-control dams and hydroelectric facilities with similar underwater inspection requirements.

Commercially available remotely operated vehicles (ROVs) can be used to conduct underwater inspections and perform minor maintenance at Corps navigation structures. ROVs are a class of maneuverable underwater robotic vehicles that are tethered via an umbilical cord to a surface operator station. The umbilical carries power and operation signals to the ROV and returns video, still images, and vehicle status and sensor data to the operator station. Using visual, sonar, and sensor information, the operator commands the ROV to maneuver around and within a structure to conduct inspections. The primary users driving ROV technology have been the offshore oil industry, the hydroelectric and nuclear power industries, various navies including the U.S. Navy, and more recently the U.S. Department of Homeland Security. Some large "work class" ROVs possess manipulators that can conduct significant maintenance operations, especially when the ROV is co-designed with the structure specifically for this purpose. We focus here mainly on ROVs used for underwater inspection, where the technology is commercially available "off the shelf" without a need to customize it to Corps tasks.

The Corps of Engineers, despite an apparent need for routine underwater inspections, has not been a major user of ROVs. Nevertheless, individual Districts or navigation facilities have purchased commercial ROVs on an ad hoc basis. We visited two such facilities, the Soo Locks at Sault Ste. Marie, MI (operated by the Detroit District), and Millers Ferry Lock and Dam, Camden, AL (operated by the Mobile District). We also visited a hydroelectric station operated by the Chelan Public Utility District, WA, which uses an ROV to inspect its facilities.

Here, we summarize the use of ROVs at the sites visited, present economic analyses of their approximate benefit/cost, and discuss the likely benefits possible from broader use of ROVs for inspecting Corps navigation structures. Note that we are not endorsing specific commercial products. Rather, we attempt to describe how the Corps can benefit from existing ROV technology and consider the additional benefits likely if the Corps were proactively to encourage technology improvements that target its specific needs.

2 ROV Use at Facilities Visited

2.1 Soo Locks

The Soo Locks (Sault Ste. Marie, MI) connect Lake Superior with Lakes Huron, Michigan, and Erie. The facility consists of three operating lock chambers with 21-ft nominal lift (Fig. 1). The MacArthur Lock (80 × 800 ft, completed in 1943) and Poe Lock (110 × 1200 ft, completed in 1968) primarily support commercial navigation. The cargo transported through the locks totals about 80–85 M tons annually, with an average of 18 cargo vessel transits per day. The thirteen 1,000-ft vessels that operate on the Great Lakes can only pass through the Poe Lock. The Davis Lock (80 × 1350 ft, completed in 1914) operates only during the summer to handle pleasure craft and tour boats. The Sabin Lock (80 × 1350 ft, completed in

Figure 1. View of Soo Locks looking west towards Lake Superior. The lift is nominally 21 ft. Commercial freighters use the two left-most locks, respectively the Macarthur Lock (80 × 800 ft) and the Poe Lock (110 × 1200 ft). The third lock from the left (60 × 800 ft) is used mainly for summer pleasure craft, and the fourth is unused. The powerhouse has a 21-MW installed capacity, and the compensation works (upper right) controls the pool elevation.

1919) is out of service. There is a proposal to replace the Davis and Sabin Locks with another 110- × 1200-ft lock chamber to accommodate 1,000-ft vessels. A dam (compensation works) consisting of 16 vertical lift gates controls the upper pool elevation, and the facility includes a powerhouse with four turbine/generators (21 MW installed capacity).

The Soo Area Field Office owns an ROV built by Deep Ocean Engineering, a Phantom 500XTL-380 purchased in 1996 (Fig. 2). The ROV measures 47 × 24 × 20 in. and weighs about 100 lb. It has two horizontal thrusters, one vertical thruster, and two lateral thrusters. Its maximum speed is about 2 kts. It also has a tilt-zoom camera, a halogen light, a depth gage, a magnetic compass, two lasers for scaling video images, and 450 ft of ¾-in.-diameter umbilical cable on a reel. It has no sonar or navigation system. The associated surface equipment includes a video monitor, VHS recorder, data-overlay system, power generator, and work space, all within a custom-made trailer. The ROV requires one driver to operate the controls in the trailer and one or two persons to handle the umbilical alongside the water.

Figure 2. Deep Ocean Engineering Phantom 500XTL-380 ROV showing a camera, lasers, light, and compass mounted to the front of the vehicle.

The ROV is used entirely for visual inspections. Visibility at the Soo Locks exceeds 30 ft in sunlight and about 10 ft under ROV lighting. No exact records are available, but the operating team estimates that they deploy the ROV 6–12 times per year, most recently to inspect piers (for erosion

damage), miter-gate sills (for debris), stop-log sills (for debris), the power canal liner (for erosion damage), and gate seals at the compensation works (for cause of leaks). The ROV has been used where conditions would be unsafe for divers, including observing miter gate closures and inspecting the compensation-works gates. The Soo personnel have navigated the ROV into filling/emptying conduits and through erosion gaps under piers to conduct inspections that would be considered hazardous penetration dives for divers. The ROV can also operate in the power canal, with a barge assist, without shutting down the turbines. They currently conduct scheduled inspections of the piers every other year (1.5–2 month duration) and plan to inspect different sections of the facility every year on a rotating basis. The ROV has also supported repair activities, including inspecting ice-boom anchors for damage prior to work conducted by divers, and providing underwater images during repairs to a hole found in the power canal liner.

The operating team is generally pleased with the ROV. However, it has some logistical shortcomings at this site. The large equipment trailer and ROV require 1–2 hrs to deploy along the southwest pier, the land side of MacArthur Lock that is the only portion of the facility accessible by standard vehicles. To deploy elsewhere, the trailer must be picked up and carried by a barge, often through a lock. Barge use is common for maintenance at the Soo, but it slows deployment by an hour or so. Two persons are needed to deploy and recover the 100-lb ROV. The protruding nose of the pier walls can make recovery awkward. Also, interleaving ROV deployment with vessel traffic is awkward: the ROV must be removed from the lock or lock approach to allow ship passage owing to strong currents from ship propellers.

The Soo Locks disbanded its dive team following the death of a diver in 1989. It now contracts for diver repair work and uses the ROV for pre-dive surveys. Soo Area personnel must still prepare dive and safety plans whenever divers are used; these are reviewed by Detroit District personnel.

2.2 Mobile District

The Mobile District operates an ROV from its field office in Tuscaloosa, AL. We observed it in use at the Millers Ferry Lock and Dam, on the Alabama River (Fig. 3), and were told about its operation at Jamie Whitten Lock and Dam on the Tennessee-Tombigbee Waterway. The locks each

Figure 3. Millers Ferry Lock and Dam on the Alabama River. The lock measures 110 x 600 ft, and the powerhouse has an installed capacity of 75 MW.

measure 110 × 600 ft and support commercial and pleasure-boat traffic. Millers Ferry has a hydroelectric plant with an installed capacity of 75 MW.

The ROV is a VideoRay Pro III XE GTO (Fig. 4) purchased in 2000 and upgraded in 2005. It measures 14 × 9 × 8 in., weighs about 8 lb and is easily deployed by one person. It has two horizontal thrusters, one vertical thruster, a forward-looking tilt color camera, a rearward-looking black and white camera, two halogen lights, a small gripper, a compass and depth gage, and a scanning sonar head. Its maximum speed is about 2 kts. The umbilical is 3/8 in. in diameter and 250 ft long and is wound on a small reel. The operator station with video monitor and drive control fits within a hand-carried case. The ROV and umbilical fit in a second hand-carried case, and the system can be assembled and deployed within a half hour. Video can be recorded on a standard hand-held video camera, and a notebook PC is used for image capture. Depending on location and flow conditions, visibility can be less than 5 ft, so the scanning sonar output is used to help maneuver the vehicle. The Mobile District ROV team consists of an operator and a person to manage the umbilical.

Figure 4. VideoRay Pro III used by the Mobile District. The operator's lower hand is holding a small gripper, and his upper hand is touching the scanning sonar head. This 8-lb ROV is easily deployed by one person.

The Mobile District team uses the ROV about 10 times per year for visual inspections of trash racks or stop-log sills to check for debris. In addition, they conduct semi-annual inspections of a repair to the roof of a filling conduit at Jamie Whitten Lock, annual inspections of District recreation areas before season opening, and opportunity-based inspections of hydro turbines, wicket gates, and lock conduits and wall joints. Vessel traffic is light, so it is easy to deploy the ROV without interfering with shipping. The team is very pleased with the performance of the ROV. Its small size allows deployment through small openings, it avoids the need for hazardous penetration dives in conduits using divers, and it is easy to deploy quickly whenever opportunities arise. The Mobile District team has also used the manipulator on their ROV to attach ropes to debris and remove it, thus avoiding the use of divers for this relatively simple task.

2.3. Chelan County Public Utility District

Chelan County Public Utility District (PUD) operates two hydroelectric dams on the Columbia River in central Washington State: the Rocky Reach and Rock Island hydro projects. Rocky Reach has 11 generators and a peak capacity of 1,400 MW (Fig. 5). The dam contains 12 spillway gates. Rock Island has 19 generators and a peak capacity of 690 MW. The dam contains 31 spillway gates.

Figure 5. Rocky Reach hydroelectric project operated by the Chelan County Public Utility District.

Chelan PUD owns a custom-made ROV purchased from Deep Ocean Engineering in 2003 (Fig. 6). They use it primarily to inspect turbine blades and upper draft tube areas for cavitation damage. This ROV replaced an earlier damaged unit and is tailored to Chelan PUD's inspection needs (Caldwell 2004). The ROV measures about 60 × 30 × 30 in. and weighs about 300 lb. It has four vectored thrusters to maneuver in the horizontal plane and three vertical thrusters to overcome downward leakage flow through the turbine. It includes a color zoom camera and a low-light black and white camera on a pan-tilt mount with angle readouts, a rearward facing camera, lights, parallel lasers for scaling forward camera images, a fiber-optic gyro for heading, vehicle pitch and roll angle sensors, a multi-frequency sonar for navigation, depth and water temperature gages, and a manipulator. The umbilical is about 0.8 in. in diameter and 500 ft long. The surface system includes a video display/recorder with data overlay plus controls to operate the ROV. The equipment is housed in a trailer, and the ROV is deployed from a basket handled by a crane. The standard operating team consists of the ROV operator, one person to oversee the video equipment, and one person to manage the umbilical.

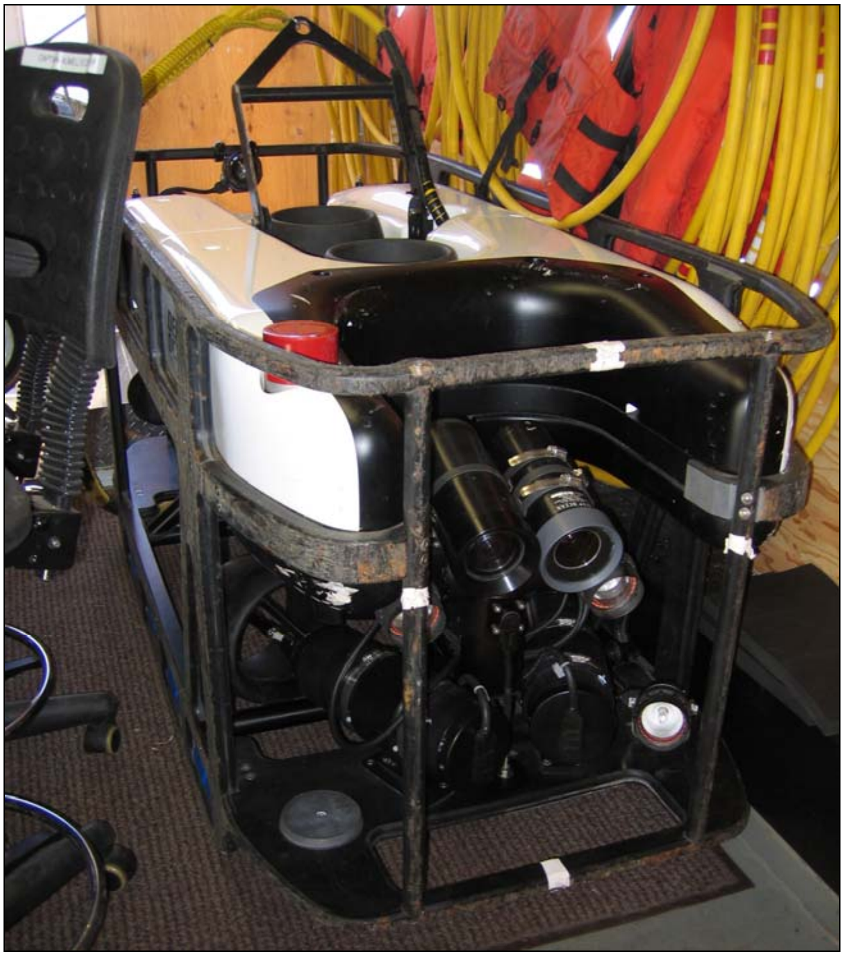

Figure 6. Front view of Chelan PUD's custom-made ROV used for turbine inspections.

Turbine inspections are conducted by navigating the ROV up the draft tube. The inspected turbine plus one turbine on either side are shut down during the inspections. The ROV can maneuver despite the leakage flow past the upstream wicket gates. The laser dots help to scale any cavitation damage found. The team tries to follow a uniform inspection sequence from one inspection interval to the next. The alternative to ROV inspection of the turbines is to dewater them, a procedure that significantly increases the inspection time. Also, although the inspections are conducted during off-peak hours, the inspections operate on a 10-minute warning basis to retrieve the ROV and restart the three generators. This helps to prevent power loss for these run-of-the-river dams. The inspections are currently conducted one month prior to a scheduled unit outage lasting longer than two weeks so that any damage observed can be repaired during the scheduled outage. The Chelan team also uses the ROV to inspect trash racks.

Chelan PUD has a seven-person dive team that is called on frequently to maintain and repair underwater equipment. The PUD prefers to use the ROV when possible to avoid the disruption and extra cost of assembling the dive team. They do use divers to inspect sills prior to setting stop logs because the divers can remove debris that the ROV cannot.

3 Benefit/Cost Analyses for ROVs

We gathered sufficient data to estimate the benefits versus cost of ROV use at the sites visited. Costs include purchase price, initial operator training costs, estimated annual maintenance and training, and deployment-based operating costs including labor. Benefits are the cost savings versus alternatives to ROV use. The contributing cost savings vary from site to site but can include costs to procure diving services (including time to prepare dive and safety plans), the cost of delays to commercial shipping, and the cost of lost hydropower production.

Tables 1–3 summarize the costs and benefits for ROV use at the three sites. We amortized ROV capital costs assuming 10-year service life and 6% per annum interest rate. All figures are 2006 dollars. Following Corps practice, we included overhead on labor (at 60%) but not on purchases or contracts. We calculated the payback period as the time required for the net annual savings to payback the total initial cost of the ROV.

Not all cost information was readily available at each site. We obtained estimates for the cost of contract divers at the sites where they are used (Soo Locks and the Mobile District). We estimated the administrative costs

Table 1. Costs and benefits of ROV use at Soo Locks.

ROV initial cost		ROV annual costs		Annual benefits (avoided costs)	
Item	Value ($)	Item	Value ($)	Item	Value ($)
ROV purchase	69,520	Maintenance	6,500	Unscheduled inspections Diver contract ($10,000) Administration ($3,200) Diver cost/inspection ($13,200) Inspections/year (8)	105,600
Trailer	12,000	Unscheduled inspections Barge ($4,000) Labor ($1,536) Cost/inspection ($5,536) Inspections/year (8)	44,288		
Initial training	9,620				
Total initial cost	91,140				
Annualized initial cost	12,383	Total ROV annual costs	50,788	Commercial shipping delays Cost/hr ($2,000) Vessels delayed (6) Average delay (8 hr) Delay cost/inspection ($96,000) Inspections/year (8) Total shipping delay costs	768,000
				Total annual benefits	873,600

Total annualized ROV costs	$63,171
Total annual benefits	$873,600
Benefit/cost	13.8
Payback (yr)	0.11

Table 2. Costs and benefits of ROV use in the Mobile District.

ROV initial cost		ROV annual costs		Annual benefits (avoided costs)	
Item	Value ($)	Item	Value ($)	Item	Value ($)
ROV purchase	30,000	Maintenance	6,500	Unscheduled inspections Diver contract ($2,000) Administration ($3,200) Diver cost/inspection ($5,200) Inspections/year (10)	52,000
Initial training	9,620	Unscheduled inspections Labor/inspection ($1,024) Inspections/year (10)	10,240		
Total initial cost	39,620				
Annualized initial cost	5,383	Scheduled conduit inspection Labor/inspection ($1,024) Inspections/year (2)	2,048	Scheduled conduit inspection Diver contract ($23,000) Administration ($3,200) Diver cost/inspection ($26,200) Inspections/year (2)	52,400
		Scheduled recreation area inspection Labor/inpection ($3,072) Inspections/year (1)	3,072	Scheduled recreation area inspection Diver contract ($6,000) Administration ($3,200) Diver cost/inspection ($9,200) Inspections/year (1)	9,200
		Total ROV annual costs	21,860		
				Total annual benefits	873,600

Total annualized ROV costs	$27,243
Total annual benefits	$113,600
Benefit/cost	4.2
Payback (yr)	0.43

Table 3. Costs and benefits of ROV use in the Chelan County Public Utility District.

ROV initial cost		ROV annual costs		Annual benefits (avoided costs)	
Item	Value ($)	Item	Value ($)	Item	Value ($)
ROV purchase	300,000	Maintenance	6,500	Turbine inspections via dewatering (Rocky Reach) Labor/inpection ($4,915) Lost power/inspection ($21,960) Inspections/year (5.5)	147,814
Trailer	12,000	Turbine inspections (Rocky Reach) Labor/inspection ($1,843) Inspections/year (5.5)	10,138		
Initial training	9,620				
Total initial cost	321,620				
Annualized initial cost	43,698	Turbine inspections (Rock Island) Labor/inpection ($1,843) Inspections/year (9.5)	17,510	Turbine inspections via dewatering (Rock Island) Labor/inpection ($4,915) Lost power/inspection ($6,300) Inspections/year (9.5)	106,544
		Total ROV annual costs	34,148		
				Total annual benefits	254,358

Total annualized ROV costs	$77,846
Total annual benefits	$254,358
Benefit/cost	3.3
Payback (yr)	1.46

for divers (procurement effort and preparation and review of dive and safety plans) based on discussions at Soo Locks and applied the same estimates for the Mobile District. We also applied the Soo Locks' average annual ROV maintenance costs to the ROVs at the other two sites. Labor rates are based on average rates for each ROV team.

At Soo Locks (Table 1) the main benefits of ROV use arise from being able to interleave inspections with vessel traffic. A lock must be closed to permit inspections with divers. Consequently, divers are only used for inspections if the lock is closed for other reasons (e.g. repairs or winter closure). Indeed, the potential cost of shipping delays is so high that routine systematic inspection of the entire facility is only feasible with an ROV.

We obtained estimates for commercial vessel traffic and delay costs at Soo Locks from a recently updated economic analysis for a replacement lock (USACE 2005). On average, 18 cargo vessels transit the locks each day, and the weighted average delay cost for these vessels is about $2,000/hr. The costs and benefits shown in Table 1 are only for the ROV to make eight unscheduled inspections per year, compared with eight inspections by divers. The benefit/cost (B/C) ratio for the ROV approaches 14:1 for these inspections, and the payback period is less than 2 months. Even with shipping delays excluded, the B/C ratio for ROV use approaches 2:1 and the payback period is less than 2 years.

These analyses do not quantify the value of more rapid response of the ROV compared with divers, say two hours versus two days, nor the savings in hydropower production for those occasions when the ROV inspects the power canal. More importantly, the ROV team conducts routine, scheduled inspections of the facility on a rotating basis. The shipping delays to use divers for a 10-day scheduled inspection during the shipping season would exceed $17M, an unacceptably large cost. Divers simply cannot be used at the Soo for systematic inspections during the shipping season.

The Soo Locks plans to replace its current ROV with a smaller unit to allow faster mobilization and easier interleaving with vessel traffic. Recent improvements to video systems also make purchasing a new unit attractive. The B/C ratio for ROV use would increase significantly for the

new unit because of its lower cost and greater utilization. The analysis presented in Table 1 is thus conservative for ROV use at Soo Locks.

In the Mobile District (Table 2), the benefits from ROV use arise from its cost-effectiveness compared with inspections by divers. Vessel traffic is light, so we have not included any delay costs. Nevertheless, at current inspection rates, the B/C ratio exceeds 4:1 for ROV use, and the payback period is less than 6 months. The B/C ratio will increase with increasing inspection rates and again does not include quantitative benefits for more rapid mobilization times. An important factor for the Mobile District is the need to inspect filling conduits at Jamie Whitten Lock and Dam. These are expensive, hazardous penetration dives for divers but are quite routine operations for the small ROV.

In the Chelan PUD, the benefits from ROV use derive from its smaller labor requirements and shorter inspection times compared with turbine inspections via dewatering. On average, the 30 turbines in the PUD are inspected every two years. ROV-based inspections use 40 fewer labor hours and save 6 hours of hydropower production per inspection. Although the cost of power is only $0.03/kW-hr, these savings are significant: the B/C ratio for ROV use exceeds 3:1, and the payback period is less than 1.5 year, despite the relatively high cost of the custom-built ROV. Indeed, the performance enhancements of this ROV pay efficiency benefits for the difficult maneuvering conditions with downward flow in the draft tubes. It also satisfies the requirement to bring turbines back online with 10 minutes notice. That is, adaptation of ROVs to key inspection tasks can certainly be worthwhile from an economic perspective.

4 Corps Inspection Needs and ROV Technology

Most of the Corps' multi-billion dollar investment in navigation facilities lies underwater during normal operation. Routine underwater inspection needs at these facilities include examinations for damage, deterioration or debris on lock miter gates and their sills, filling and emptying valves and conduits, pier structures, dam gates and sills, stop-log sills, dam structural components and sealing systems, and hydroelectric facilities and components. Emergency or unplanned underwater inspection needs encompass entire facilities.

ROVs offer simple, cost-effective, and expedient ways to conduct underwater inspections of these facilities and decrease the need for divers to conduct potentially hazardous inspections. Their benefit/cost ratios are large compared with using divers for inspections and increase with increasing inspection rates. Thus, ROVs offer the tools needed to improve overall asset management in the Corps by increasing inspection rates, identifying problems before they become chronic, aiding the design of solutions prior to scheduled maintenance, and monitoring the efficacy of the repairs. Collectively, these activities will help to reduce expensive, unplanned maintenance at Corps navigation facilities.

ROVs can also conduct inspections during construction and repair operations in conditions that would be hazardous to divers, such as placing concrete or installing gates. "In-the-wet" construction and repair operations are becoming more common in the Corps, and ROVs can provide critical quality-control information while the work is still underway.

For most inspections, the valuable data gathered by ROVs derive from their cameras. The ROV platform is primarily a device to maneuver "eyes" underwater to inspect areas of concern. The operator and facility engineer then make judgments pertaining to the nature of the concern and any changes from previous inspections. High-quality cameras (video and pictures) and easy-to-maneuver platforms are essential technologies. Small, so-called "micro" ROVs satisfy these needs. Compared with larger platforms, they also have the advantages of low capital cost, rapid

deployment, and two-person teams. Commercial vendors can supply micro ROVs with initial costs below $30K. Most Corps navigation facilities should own a micro ROV to conduct routine inspections; two or more small locks in close proximity could potentially share one. Facilities or Districts with specialized inspection needs, such as those with hydropower plants, could justify acquiring ROVs adapted to these needs.

The Corps overall could also encourage the development or adaptation of ROV technologies to meet its inspection needs more efficiently. A key need is to quantify precisely the location of an ROV image within the facility and to return to that same location for repeat inspections. At the sites visited, the operators navigate and orient the ROV primarily with video feedback. The Mobile District operator also navigates with scanning sonar to overcome poor visibility conditions. Experience in identifying landmarks within passages becomes critical to identifying the location of an image and returning to that location when required.

Commercial acoustic navigation systems exist that improve ROV navigation precision. These systems place one or more acoustic sources at known locations and rely on the phase or timing differences of pulses received at the ROV to determine its location in real time. They have been used to navigate ROVs in open-water conditions, with position accuracies below 3 ft achievable. Their performance within the walls of lock chambers, filling/emptying conduits, and draft tubes is as yet unknown. Software available with these systems can place the ROV within a 3-D virtual image of the site. The Corps could collaborate with vendors to adapt these systems and their software to provide real-time displays of ROV location and orientation within a 3-D CAD image of the facility. This would greatly improve the efficiency of ROV navigation and the reliability of repeat inspections.

A complementary technology is software to archive images from inspections keyed to the image locations, similar to geo-referenced levee inspection systems. This would help operators and engineers assess whether conditions are deteriorating over time and to assess the performance of repairs at specific locations.

A simple existing technology—laser projection to scale images—already allows engineers to quantify damage observed on images. Scaled images allow engineers to design more effective solutions prior to repair

operations and to track the evolution of damage or the performance of the repair over time. The Corps could encourage vendors to adapt software to process these images automatically. Additionally, ultrasonic, magnetic, or other sensor technologies could be added to ROVs to complement in-the-wet visual inspections of concrete and metal structures.

In general, the ROV industry is small and still evolving. Manufacturers of the platforms, as well as suppliers of the imaging and navigation systems, are likely to be eager to work with the Corps to adapt systems to its needs and thereby increase the overall size of the industry.

If ROV use for inspections becomes widespread in the Corps, a logical extension is to attempt progressively more ambitious repairs using ROVs. Compared to using divers, repairs using ROVs could be highly cost effective and more expedient. This has been the trend in the offshore oil industry, where platform and sub-sea system designs have co-evolved with increasing ROV capability to conduct repairs. However, the functionality of a manipulator generally increases with size, so that larger ROVs would be needed to conduct repairs compared with inspections. Nevertheless, this option could be pursued systematically over the long term to enhance the contribution of ROVs to Corps asset management.

5 Conclusions

The vast majority of the Corps' multi-billion dollar investment in navigation structures lies underwater during normal operation, making routine inspections difficult. The significant increase in unscheduled maintenance at these structures suggests that underwater inspections are not occurring as frequently as prudence would dictate.

We visited two Corps facilities and one public utility district that currently use ROVs for routine inspections. We documented how the ROVs are used and compared their costs with those based on inspections using divers or dewatering. In each case, benefits from reduced labor costs, shipping delays, and lost power production far exceed the amortized costs of the ROVs. Indeed, the payback period for purchasing a new ROV can easily be less than one year. In addition, ROVs can be mobilized very quickly and with little incremental cost, so that they encourage more frequent inspections of facilities.

Existing ROV technology can contribute immediately to improved Corps asset management and public safety assurance through increased rates of underwater inspections at navigation structures. Fundamentally, an ROV provides maneuverable "eyes" underwater to allow operators and engineers to identify likely damage before it becomes chronic, to scope necessary repairs, and to assess the efficacy of these repairs. They can also assist with quality-control inspections during in-the-wet construction and repair operations. Huge savings are possible if ROVs can help to identify maintenance or quality-control problems before these problems trigger unplanned closures for repairs.

Their benefits are so great that most Corps navigation facility should own a small ROV, costing about $30K, to conduct routine underwater inspections. Two or more small locks in close proximity could potentially share an ROV. In addition, the Corps should encourage, in partnership with commercial developers, near-term hardware and software improvements to enable efficient ROV navigation within Corps structures and to integrate real-time position, sensor data, and visual images within 3-D virtual representations of these structures. These improvements would allow rapid transfer of inspection results to facility engineers and

managers to assist with cost-effective maintenance decisions. Longer-term technology investment could lead to ROVs specifically adapted for conducting timely and cost-effective maintenance at of Corps navigation structures.

References

Caldwell, B. 2004. Under inspection. *International Water Power and Dam Construction* December, 28–30.

Kidby, M. 2006. Personal communication. Headquarters, U.S. Army Corps of Engineers, 18 April.

USACE. 2005. *Final limited reevaluation report, Replacement lock – Sault Ste. Marie, Michigan. Appendix B, Economic analysis.* Revised August 2005. B1–B98. U.S. Army Corps of Engineers, Detroit District.

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14. ABSTRACT

The U.S. Army Corps of Engineers operates numerous navigation locks and dams across the country. Age and lack of funds to maintain these structures has led to significant increases in unscheduled outages. Dewatering provides the best inspection opportunity but is costly and halts navigation traffic. Diver inspections are costly, and safety is an issue. Frequent underwater inspections using remotely operated vehicles (ROVs) would help reduce the number and severity of unscheduled outages at low cost, with little impact on navigation and few safety concerns. ROV use was documented at two Corps facilities and one public utility district and their costs were compared with inspections using divers or dewatering. In each case, benefits from reduced labor costs, shipping delays, and lost power production far exceed the amortized costs of the ROVs. The payback period for purchasing an ROV can be less than one year, and their easy deployment encourages more frequent inspections. ROV technology can immediately help to improve Corps asset management and public safety assurance through increased underwater inspections. Most Corps navigation facilities should own a small ROV, costing about $30K, to conduct visual inspections. Also, the Corps should partner with vendors to improve ROV internal navigation and to integrate real-time position, sensor data, and visual images within 3-D virtual representations of its structures.

15. SUBJECT TERMS
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Inspections
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Remotely operated vehicles

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